INFRARED SPECTROSCOPY OF A MASSIVE OBSCURED STAR CLUSTER IN THE ANTENNAE GALAXIES (NGC 4038/4039) WITH NIRSPEC

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Abstract

We present infrared spectroscopy of the Antennae Galaxies (NGC 4038/4039) with NIRSPEC at the W. M. Keck Observatory. We imaged the star clusters in the vicinity of the southern nucleus (NGC 4039) in $0''.39$ seeing in K-band using NIRSPEC's slit-viewing camera. The brightest star cluster revealed in the near-IR ($M_K(0) \simeq -17.9$) is insignificant optically, but coincident with the highest surface brightness peak in the mid-IR ($12-18\mu$m) ISO image presented by Mirabel et al. (1998). We obtained high signal-to-noise $2.03-2.45$ μm spectra of the nucleus and the obscured star cluster at R ~ 1900.

The cluster is very young (age ~ 4 Myr), massive (M $\sim 16 \times 10^6$ $M_\odot$), and compact (density ~ 115 $M_\odot$ pc^{-3} within a 32 pc half-light radius), assuming a Salpeter IMF ($0.1-100$ $M_\odot$). Its hot stars have a radiation field characterized by $T_{\rm eff} \sim 39,000$ K, and they ionize a compact H II region with $n_e \sim 10^4$ cm^{-3}. The stars are deeply embedded in gas and dust ($A_V \sim 9-10$ mag), and their strong FUV field powers a clumpy photodissociation region with densities $n_H \gtrsim 10^5$ cm^{-3} on scales of ~ 200 pc, radiating $L_{H_2 1-0\ S(1)} = 9600$ $L_\odot$.

Key words: Galaxies: individual (NGC4038/39, Antennae Galaxies) – Galaxies: star clusters – Galaxies: H II regions

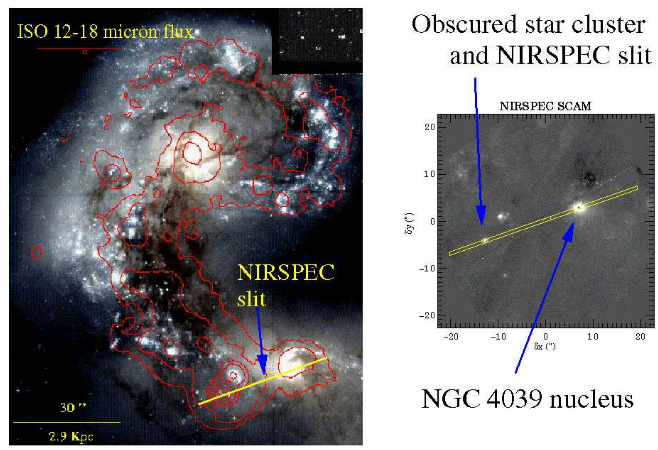

Figure 1. HST image of the Antennae overlaid with ISO 12–18 μm contours (Mirabel et al. 1998), and NIRSPEC K band image showing the slit position and several star clusters in the field.

1. Introduction

The Antennae (NGC 4038/4039) are a pair of disk galaxies in an early stage of merging which contain numerous massive super star clusters (SSCs) along their spiral arms and around their interaction region (Whitmore & Schweizer 1995; Whitmore et al. 1999). The molecular gas distribution peaks at both nuclei and in the overlap region (Stanford et al. 1990), but the gas is not yet undergoing a global starburst typical of more advanced mergers (Nikola et al. 1998). Star formation in starbursts appears to occur preferentially in SSCs. We chose to observe the Antennae because their proximity permits an unusually detailed view of the first generation of merger-induced SSCs and their influence on the surrounding interstellar medium.

The Infrared Space Observatory (ISO) $12-18$ μm image showed that the hot dust distribution is similar to that of the gas, but peaks at an otherwise inconspicuous point on the southern edge of the overlap region (Mirabel et al. 1998; see Wilson 2000). This powerful starburst knot is also a flat-spectrum radio continuum source (Hummel & van der Hulst 1986) and may be associated with an X-ray source (Fabbiano et al. 1997). We imaged the region around this knot, and discovered a bright compact star cluster coincident with the mid-IR peak. We obtained moderate-resolution (R $\sim$ 1900) K-band spectra of both the obscured cluster and the NGC 4039 nucleus.

2. Observations & Data Reduction

NIRSPEC is a new facility infrared ($0.95-5.6\mu$m) spectrometer for the Keck-II telescope, commissioned during April through July, 1999 (McLean et al. 1998). It has a cross-dispersed cryogenic echelle with R $\sim 25,000$, and a low resolution mode with R ~ 2000. The spectrometer de-

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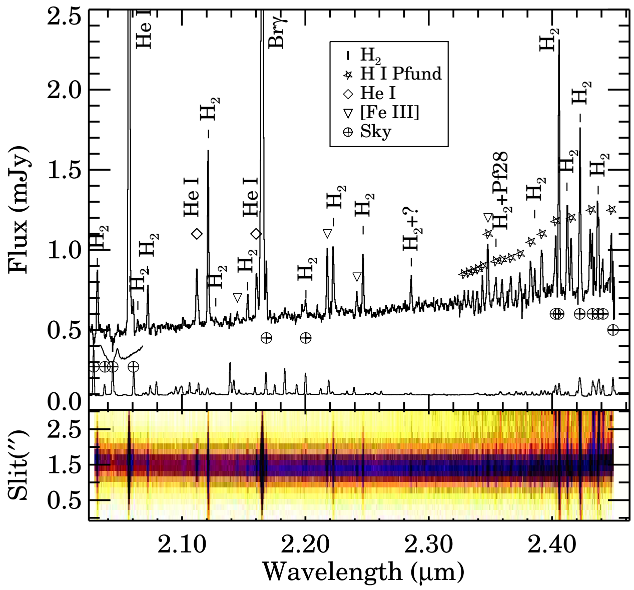

Figure 2. NIRSPEC spectrum of the obscured star cluster shows nebular and fluorescent H_2 emission with a continuum rising toward the red. Scaled sky counts are plotted at 0.1 mJy. ω-shaped curve represents an atmospheric CO_2 band at 2.05 μm.

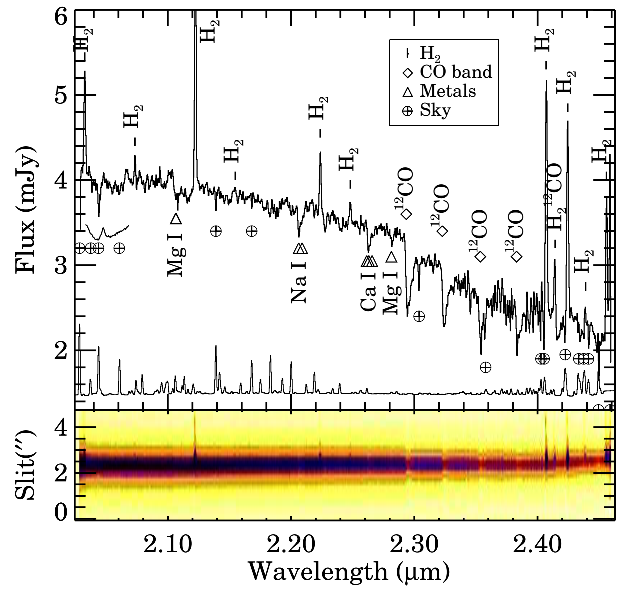

Figure 3. NIRSPEC spectrum of NGC 4039 nucleus shows extended collisionally excited H_2 emission and a strong stellar continuum marked by photospheric absorption. No Brγ is present. Scaled sky counts are shown at 1.5 mJy.

tector is a 1024 × 1024 InSb ALADDIN focal plane array, and the IR slit-viewing camera detector is a 256 × 256 HgCdTe PICNIC array.

We observed the Antennae with NIRSPEC during the June 1999 commissioning run. Figure 1 shows the HST and ISO image of Mirabel et al. (1998) together with NIRSPEC slit-viewing camera (SCAM) images at 2 μm; the SCAM images reveal that the mid-IR ISO peak is a bright (K = 14.6) compact star cluster located $20''.4$ east and $4''.7$ north of the K-band nucleus. This cluster is associated with a faint (V = 23.5) red (V−I = 2.9) source (# 80 in Whitmore & Schweizer 1995) visible with Space Telescope (Whitmore & Zhang, private communication). We obtained low resolution ($R \simeq 1900$) $\lambda \simeq 2.03 - 2.45$ μm spectra through a $0''.57 \times 42''$ slit at PA=77^o located on the obscured star cluster and the nucleus of NGC 4039, for a total integration time of 2100 s. We reduced the data following the standard procedure, described in more detail by Gilbert et al. (2000). Reduced spectra are shown in Figures 2 and 3.

3. Massive Star Cluster

The cluster spectrum is characterized by strong emission lines[1] and a continuum (detected with SNR ≃ 15) dominated by the light of hot, blue stars and dust. The nebular emission lines are slightly more extended than the continuum, and the H_2 emission is even more extended. This suggests a picture in which hot stars and dust are embedded in a giant compact H II region surrounded by clumpy (see §3.2) clouds of obscuring gas and dust whose surfaces are ionized and photodissociated by FUV photons escaping from the star cluster.

For a distance to the Antennae of 19 Mpc (H_0=75 km s^{-1} Mpc^{-1}, $1''$= 93 pc) (Whitmore et al. 1999), we find that the cluster has $M_K = -16.8$. We estimate the screen extinction to the cluster by assuming a range of $(V-K)_0 \simeq 0-1$ as expected from Starburst99 models (Leitherer et al. 1999), and that $A_K = 0.11\ A_V$ (Rieke & Lebofsky 1985). We find $A_V = 9-10$ mag, which implies $M_K(0) = -17.9$, adopting $A_K = 1.1$ (which is confirmed by our analysis of the H II recombination lines in §3.1). We can use the intrinsic brightness along with the Lyman continuum flux inferred from the de-reddened Brγ flux (3.1×10^{-14} erg s^{-1} cm^{-2}), $Q(H^+)_0 = 1.0 \times 10^{53}$ photons s^{-1}, to constrain the cluster mass and age. Using instantaneous Starburst99 models we find a total mass of $\sim 7 \times 10^6$ $M_\odot$ (with ∼ 2600 O stars) for a Salpeter IMF extending from 1 to 100 $M_\odot$, and an age of ∼ 4 Myr. This age is consistent with the lack of photospheric CO and metal absorption lines from red supergiants and other cool giants, which would begin to contribute significantly to the 2 μm light at an age of ∼ 7 Myr (Leitherer et al. 1999). The cluster's density is then about 115 $M_\odot$ pc^{-3} for stars of 0.1−100 $M_\odot$ within a half-light radius of 32 pc. This density is 30 times less than that of the LMC SSC, R136 (within a radius of 1.7 pc, assuming a Salpeter proportion of low-mass stars) (Hunter

[1] A table of measured line fluxes is available electronically from http://astro.berkeley.edu/∼agilbert/antennae.

et al. 1995). Thus the Antennae cluster may be a complex of clusters rather than one massive cluster.

3.1. Nebular Emission

The cluster spectrum features a variety of nebular lines that reveal information about the conditions in and around the gas ionized gas by the cluster, which in turn allows us to constrain the effective temperature of the ionizing stars.

We detected H I Pfund series lines from Pf 19 to Pf 38, which allow us to infer the extinction across the K window. We display the Pfund fluxes relative to that of Brγ in Figure 4, where filled symbols give fluxes for the blends Pf 28+H_2 2$-$1 S(0) and Pf 29+[Fe III]. They fall well above the other points, which follow closely the theoretical expectation for intensities relative to Brγ (solid curve) with no reddening applied, for a gas with $n_e = 10^4$ cm^{-3} and $T_e = 10^4$ K (Hummer & Storey 1987). Excluding the two known blends, the best-fit foreground screen extinction is $A_K = 1.1 \pm 0.3$ mag (dashed curve), assuming the extinction law of Landini et al. (1984) and evaluated at 2.2 μm. We consider this an upper limit on A_K because a close look at the spectrum shows that the points above the dashed line in Figure 4 for Pf 22$-$24 at 2.404, 2.393, and 2.383 μm may also be blended or contaminated by sky emission, implying a lower A_K and a much better fit to the theory. Hence the majority of the extinction to the cluster is bypassed by observing it in K band.

The ratios of [Fe III] 2.146 μm and 2.243 μm lines to [Fe III] 2.218 μm are nebular density diagnostics, consistent with a fairly high density, $n_e = 10^{3.5} - 10^4$ cm^{-3}. (See Gilbert et al. (2000) for more detail.) The He I line ratios can be used to infer nebular temperature T_e, and are fairly insensitive to n_e. We find the ratio He I 2.1128+2.1137 μm/He I 2.0589 μm = 0.052 $\pm$ 0.003, which for n_e=10^4 cm^{-3} is consistent with $T_e = 17,500 \pm 800$ K (Benjamin et al. 1999). However this is much hotter than typical nebular temperatures, and may indicate some non-nebular contribution from hot stars to the line emission.

The He I 2.0589 μm/Br γ ratio is an indicator of the $T_{\rm eff}$ of hot stars in H II regions (Doyon et al. 1992), although it is sensitive to nebular conditions such as the relative volumes and ionization fractions of He^+ and H^+, geometry, density, dustiness, etc. (Shields 1993). Doherty et al. (1995) studied H and He excitation in a sample of starburst galaxies and H II regions. For starbursts they found evidence for high-$T_{\rm eff}$, low-n_e ($\sim 10^2$ cm^{-2}) ionized gas from He I 2.0589 μm/Br γ ratios of 0.22 to 0.64. The ultra-compact H II regions were characterized by higher ratios (0.8$-$0.9) and higher densities, $\sim 10^4$ cm^{-3}. The cluster has a flux ratio of 0.70, a value between the two object classes of Doherty et al. (1995). Assuming the line emission is purely nebular, this ratio is consistent with a high-density (10^4 cm^{-3}) model of Shields (1993) (also indicated by the [Fe III] emission), and implies $T_{\rm eff} \simeq 39,000$ K for the assumed model parameters.

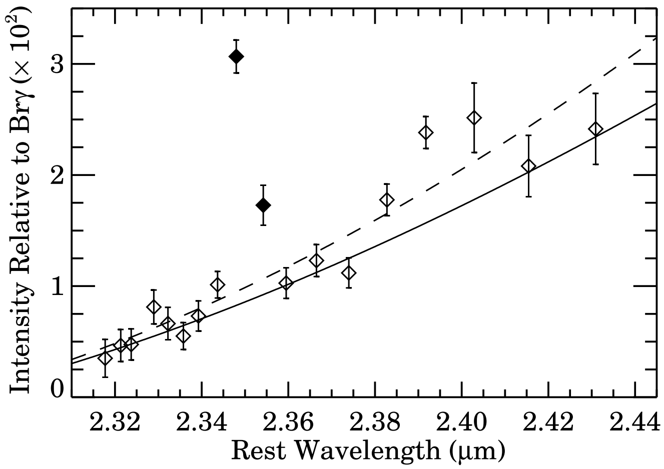

Figure 4. Pfund line fluxes relative to Brγ flux (1.05×10^{-14} *erg s^{-1}cm^{-2}). Solid curve is unextincted theoretical curve for $n_e = 10^4$ cm^{-3}, $T_e = 10^4$ K (Hummer & Storey 1987). Filled symbols represent lines that are known blends, and the dashed curve shows theoretical fluxes with the best-fit extinction $A_K = 1.1$ mag.*

The cluster has properties more like those of a compact H II region than a diffuse one. It appears to be a young, hot, high-density H II region, one of the first to form in this part of the Antennae interaction region.

3.2. Molecular Emission

The spectrum shows evidence for almost pure UV fluorescence excited by FUV radiation from the O & B stars; the strong, vibrationally excited 1$-$0, 2$-$1 & 3$-$2 H_2 emission has $T_{\rm vib} \gtrsim 6000$ K and $T_{\rm rot} \simeq 970$, 1600, and 1800 K, respectively, and weak higher-v (6$-$4, 8$-$6, 9$-$7) transitions are present as well. The H_2 lines are extended over $\simeq$ 200 pc, about twice the extent of the continuum and nebular line emission, so a significant fraction of the FUV (912$-$1108 Å) light escapes from the cluster to heat and photodissociate the local molecular ISM.

We compared the photodissociation region (PDR) models of Draine & Bertoldi (1996) with our data by calculating reduced χ^2_ν. Models with high densities ($n_H = 10^5$ cm^{-3}), moderately warm temperatures (T = 500 to 1500 K at the cloud surface), and high FUV fields ($G_0 = 10^3 - 10^5$ times the mean interstellar field) can reasonably fit the data. Figure 5 shows χ^2_ν contours for all models projected onto the $n_H$$-$$G_0$ plane. The best-fit Draine & Bertoldi model is n2023b, which has $n_H = 10^5$ cm^{-3}, T = 900 K, and G_0 = 5000. We fit 22 H_2 lines, excluding 3$-$2 S(2) 2.287 μm because it appears to be blended with a strong unidentified nebular line at 2.286 μm found in higher-resolution spectra of planetary nebulae (Smith et al. 1981). The weak high-v transitions are all underpredicted by this model, and appear to come from lower-

density gas ($n_H \lesssim 10^3 - 10^4$ cm^{-3}) exposed to a weaker FUV field ($G_0 \lesssim 10^2 - 10^3$).

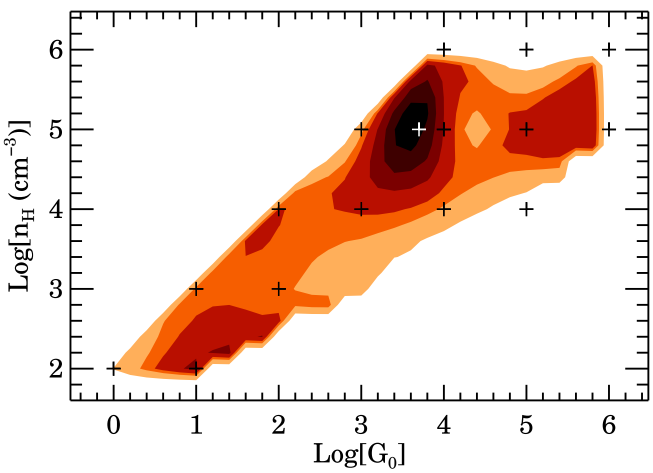

Figure 5. Comparison of H_2 line strengths with PDR models. Contours of χ^2_ν for 22 lines projected onto $n_H - G_0$ plane peak at $n_H \sim 10^5$ cm^{-3} and $G_0 \sim 5000$. Model points (+) are for T_0 = 300 − 2000 K. White + marks best-fit PDR model of Draine & Bertoldi (1996), with T_0 = 900 K and $\chi^2_\nu = 9.3$. Contours are 50, 25, 20, 15, 12, 10.

The ortho/para ratio of excited H_2 determined from the relative column densities inferred from 1−0 S(1) and S(0) lines is 1.62±0.07. This is consistent with the ground state v=0 H_2 being in LTE with ortho/para ratio of 3 if the FUV absorption lines populating the non-LTE excited states are optically thick (Sternberg & Neufeld 1999). Indeed, the best-fit PDR models have temperatures that are comparable with T_{rot} in the lowest excited states.

If the extent of the H_2 emission indicates that the mean-free path of a FUV photon is $\sim$ 200 pc, then $\langle n_H \rangle$ = 3 cm^{-3} for a Galactic gas-to-dust ratio, while in the PDR(s) $n_H = 10^4 - 10^6$ cm^{-3}. This implies that the molecular gas is extremely clumpy, which is consistent with the range of densities inferred from the detection of anomalously strong v = 8−6 H_2 emission.

4. Conclusions

The highest surface brightness mid-IR peak in the ISO map of the Antennae Galaxies is a massive ($\sim 16\times10^6$ $M_\odot$), obscured ($A_V \sim 9 - 10$), young (age $\sim$ 4 Myr) star cluster with half-light radius $\sim$ 32 pc, whose strong FUV flux excites the surrounding molecular ISM on scales of up to 200 pc. The cluster spectrum is dominated by extended fluorescently excited H_2 emission from clumpy PDRs and nebular emission from compact H II regions. In contrast, the nearby nucleus of NGC 4039 has a strong stellar spectrum dominated by cool stars, where the only emission lines are due to shock-excited H_2. These observations confirm the potential of near-infrared spectroscopy for exploration and discovery with the new generation of large ground-based telescopes. Our ongoing program of NIRSPEC observations promises to reveal a wealth of information on the nature of star formation in star clusters.

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References

Benjamin, R.A., Skillman, E.D., Smits, D.P., 1999, ApJ, 514, 307
Doherty, R.M., Puxley, P.J., Lumsden, S.L. et al. 1995, MNRAS, 277, 577
Doyon, R., Puxley, P.J., Joseph, R.D., 1992, ApJ, 397, 117
Draine, B. T., Bertoldi, F., 1996, ApJ, 468, 269
Fabbiano, G., Schweizer, F., Mackie, G., 1997, ApJ, 478, 542
Gilbert, A.M., Graham, J.R., McLean, I. S. et al. 2000, to appear in ApJL
Hummel, E., van der Hulst, J.M., 1986, A&A, 155, 151
Hummer, D.G., Storey, P.J., 1987, MNRAS, 224, 801
Hunter, D.A., Shaya, E.J., Holtzman, J.A. et al. 1995, ApJ, 448, 179
Landini, M., Natta, A., Salinari, P. et al. 1984, A&A, 134, 284
Leitherer, C., Schaerer, D., Goldader, J.D. et al. 1999, ApJS, 123, 3
McLean, I.S., Becklin, E.E., Bendiksen, O. et al. 1998, Proc. SPIE, 3354, 566
Mirabel, I.F., Vigroux, L., Charmandaris, V. et al. 1998, A&A, 333, L1
Nikola, T., Genzel, R., Herrmann, F. et al. 1998, ApJ, 504, 749
Rieke, G.H., Lebofsky, M.J., 1985, ApJ, 288, 618
Shields, J.C., 1993, ApJ, 419, 181
Smith, H.A., Larson, H.P., Fink, U., 1981, ApJ, 244, 835
Stanford, S.A., Sargent, A.I., Sanders, D.B. et al. 1990, ApJ, 349, 492
Sternberg, A., Neufeld, D. A., 1999, ApJ, 516, 371
Whitmore, B.C., Schweizer, F., 1995, AJ, 109, 960
Whitmore, B.C., Zhang, Q., Leitherer, C. et al. 1999, AJ
Wilson, C., 2000, these proceedings